Acoustic studies of the large scale ocean circulation

Detailed knowledge of ocean circulation and its transport properties is prerequisite to an understanding of the earth's climate and of important biological and chemical cycles. Results from two recent experiments, THETIS-2 in the Western Mediterranean and ATOC in the North Pacific, illustrate the use of ocean acoustic tomography for studies of the large scale circulation. The attraction of acoustic tomography is its ability to sample and average the large-scale oceanic thermal structure, synoptically, along several sections, and at regular intervals. In both studies, the acoustic data are compared to, and then combined with, general circulation models, meteorological analyses, satellite altimetry, and direct measurements from ships. Both studies provide complete regional descriptions of the time-evolving, three-dimensional, large scale circulation, albeit with large uncertainties. The studies raise serious issues about existing ocean observing capability and provide guidelines for future efforts.

Acoustic studies of the large scale ocean circulation

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The ocean stores and transports vast quantities of heat, fresh water, carbon, and other materials, and its circulation plays an important role in determining both the Earth's climate and fundamental processes in the biosphere. Understanding the development of climate and important biological cycles therefore requires detailed knowledge of ocean circulation and its transport properties. That in turn requires observing and modeling a global scale turbulent flow field so as to adequately depict its complex temporal and spatial evolution. Studying climate-scale variability is very difficult, however, because it is masked by an intense 100 km spatial scale variability (the so-called mesoscale) as well as higher frequency internal waves. Two recently developed observational methods, satellite altimetry and acoustic tomography are especially suitable for detecting climate-scale changes because they provide large-scale averages.

Satellite altimetry depends on the travel time of radio waves reflected at the sea surface to measure the sea surface elevation relative to the geoid, that is, relative to the particular gravitational equipotential to which the sea surface would conform if it were at rest with no forces acting on it. Changes in elevation result from local exchange of mass and heat with the atmosphere through the sea surface and from lateral water movements. In general terms, surface elevation and its slope provide a dynamical surface boundary condition on the general circulation.

The second observational system, ocean acoustic tomography, relies on the travel time of sound waves through the (electromagnetically opaque) ocean interior. Tomography integrates the oceanic state along many paths through a volume of fluid by transmitting sound pulses from sources to receivers. Perturbations in travel time of acoustic pulses are dominated by temperature perturbations. Hence acoustic tomography can act as a large scale ocean thermometer and provide accurate measurements of heat content, an important climate variable.

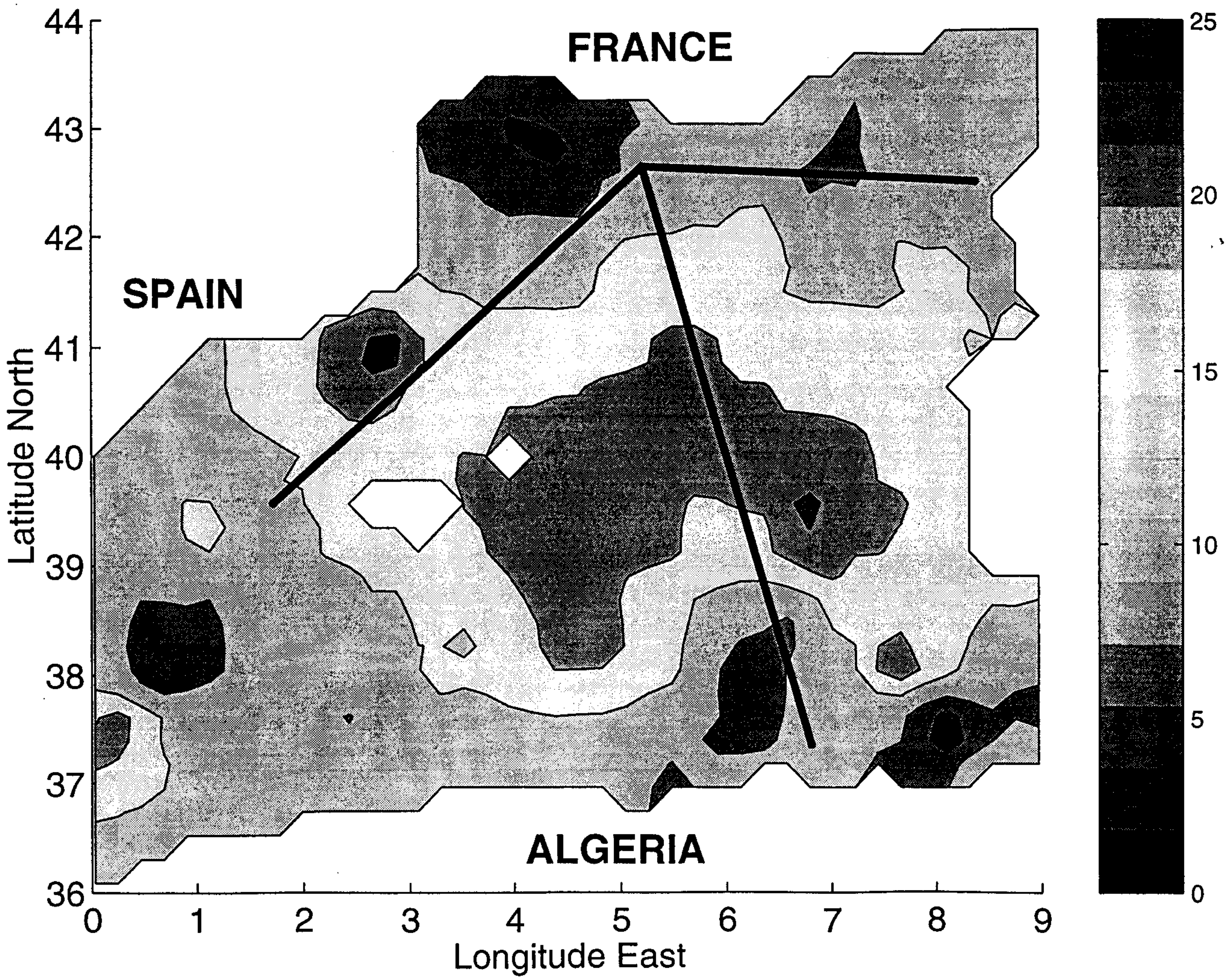
The combined power of these two technologies for studying the large scale circulation has been demonstrated in two recent experiment, THETIS-2 in the Western Mediterranean and ATOC in the North Pacific. In both experiments, the altimetric and acoustic data are combined with general circulation models, meteorological analyses, and direct measurements from ships. These model/data combinations provide regional descriptions of the time-evolving state of the ocean which are more complete and accurate than either the model or the data alone. They are an analogue of what is required globally to address various climate related questions, for initializing seasonal to interannual climate predictions, as well as for navigation and exploration purposes.

Figure Captions:

Figure 1: Study area for the THETIS-2 experiment in the Western Mediterranean. The colored contours indicate sea surface height change in centimeters between March and September 1994 from the TOPEX/POSEIDON altimeter. The black lines are acoustic tomography sections. The sea surface height increase from March to September is indicative of seasonal warming but includes complex contributions from changes in wind forcing, from evaporation and precipitation, from river runoff, and from flows through the Straits of Sicily and Gibraltar. Acoustic tomography and a numerical model of the circulation are used to separate the respective contributions to sea level anomaly.

Figure 2: The ATOC acoustic array (black lines) is superimposed on a map indicating sea surface height variability in centimeters obtained from TOPEX/POSEIDON altimetric measurements. About half of the sea surface height variability represents seasonal thermal changes within the ocean. But changes in sea surface height also include complex contributions from other processes, with the acoustic data providing a stable spatial average of heat content which it is otherwise difficult to obtain.

Figure 3: This figure illustrates results from a model/data combination which permits a complete description of the time evolving state of the ocean. The colored contours indicate temperature change averaged over the top 4000~m, from January 1996 to January 1997 (white regions indicate depths less than 4000~m). The arrows indicate the corresponding change in velocity at 610~m, the largest change being about 5 cm/s. This type of results are being used to study the large scale ocean circulation and to understand the role of the oceans in climate and climate change.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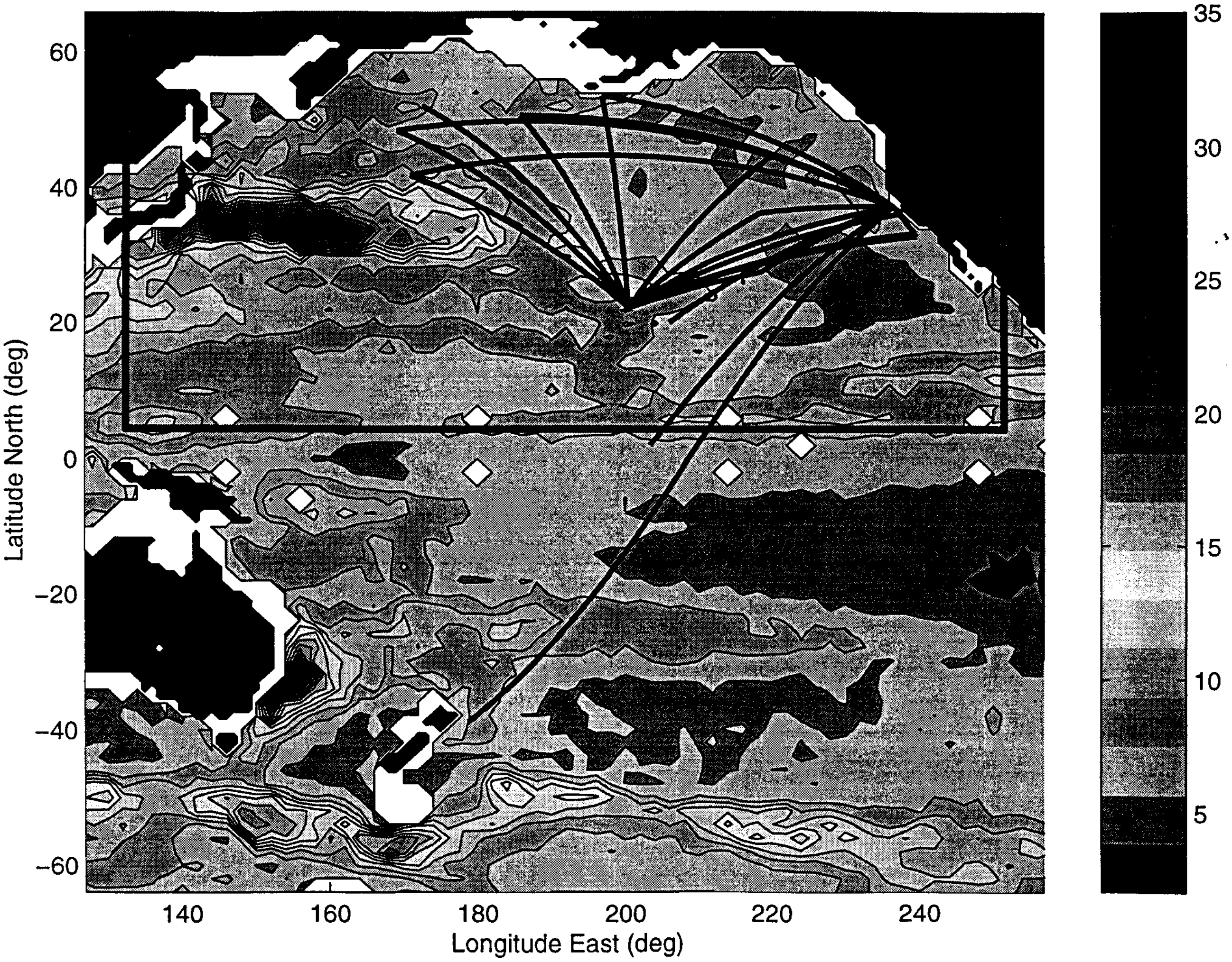

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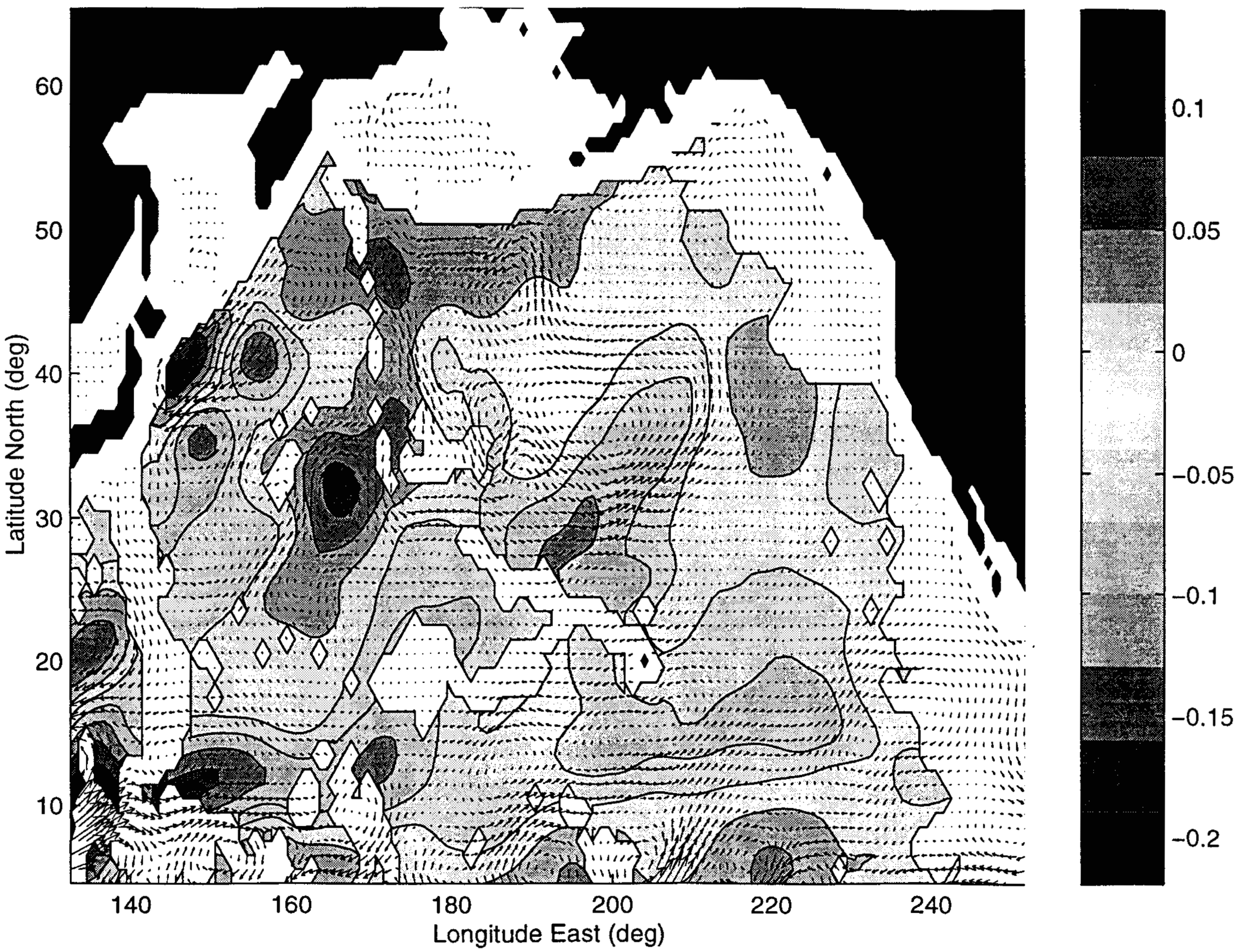
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estimating baroclinic errors in OGCMs

using ATOC

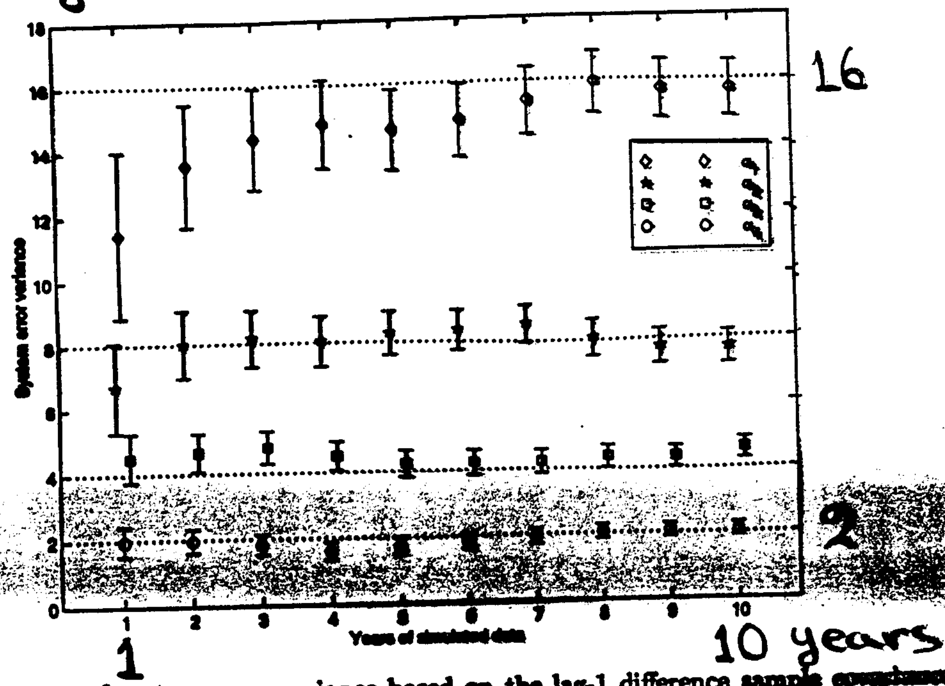


Figure 4. Estimates of system error variance based on the lag-1 difference sample covariance, $\hat{\mathbf{D}}_1$, for simulated acoustic tomography data. Dotted lines indicate the values of $\alpha_1 \ldots \alpha_4$ used to generate the data. The error bars represent the standard error of the estimates. The figure demonstrates the increasing accuracy of the algorithm with increasing number of measurements.

using TOPEX POSEIDON

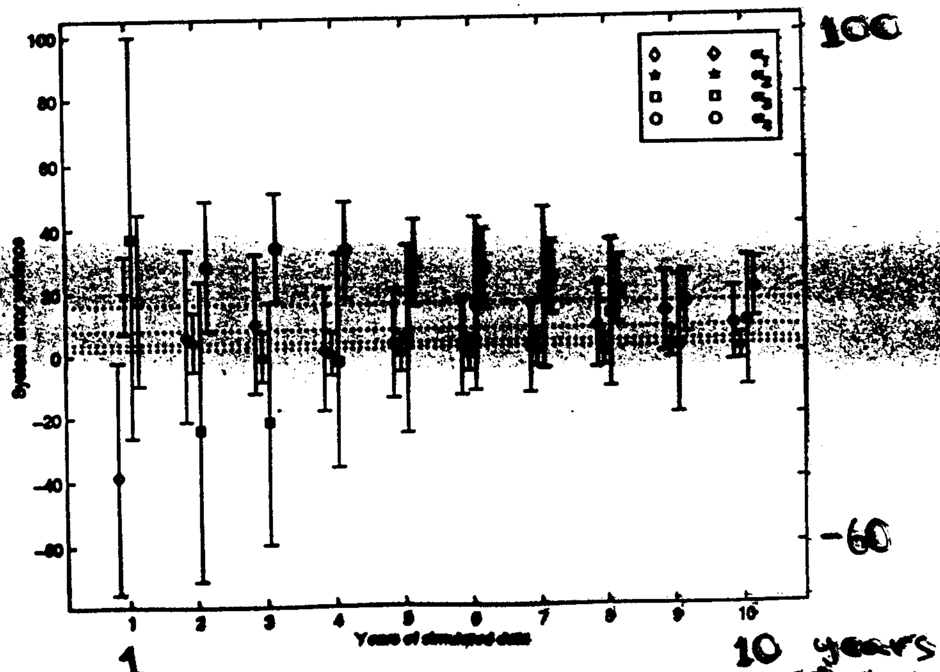


Figure 5. Estimates of system error variance based on the diagonal elements of $\hat{\mathbf{D}}_1$ for simulated altimeter data. Dotted lines indicate the prior variances used to generate the data. Error bars represent the standard uncertainty of the estimates and they can be compared to those of Fig. 4 which was created using simulated acoustic data. The large error bars associated with the altimetric estimates suggest that altimeter data are ill-suited to the estimation of baroclinic GCM errors.

(Chechelnitsky and Menemenlis '98)

1. THETIS-2 experiment
(Western Mediterranean)

2. ATOC experiment
(North Pacific)

3. Global-ocean data assimilation system
(SCRIPPS, MIT, JPL effort)

Global-ocean data assimilation system

(SCRIPPS, MIT, JPL effort)

Objective

Estimate global time-evolving ocean circulation by combining modern large scale data sets and general circulation models.

Science Goals

Understand the basic state of the ocean, its variability and its interaction with the atmosphere.

Estimate meridional fluxes and flux divergences of heat, fresh water, carbon, and nutrients.

Study global physical processes linking ocean with changing atmosphere, and their role in climate variability.

PRESENT STATUS

completed

2°, 20-level, 1-year adjoint model computation
(http://puddle.mit.edu/[illegible])

2°×1° / 10°×5° approximate Kalman filter
(Fukumori et al., in press)

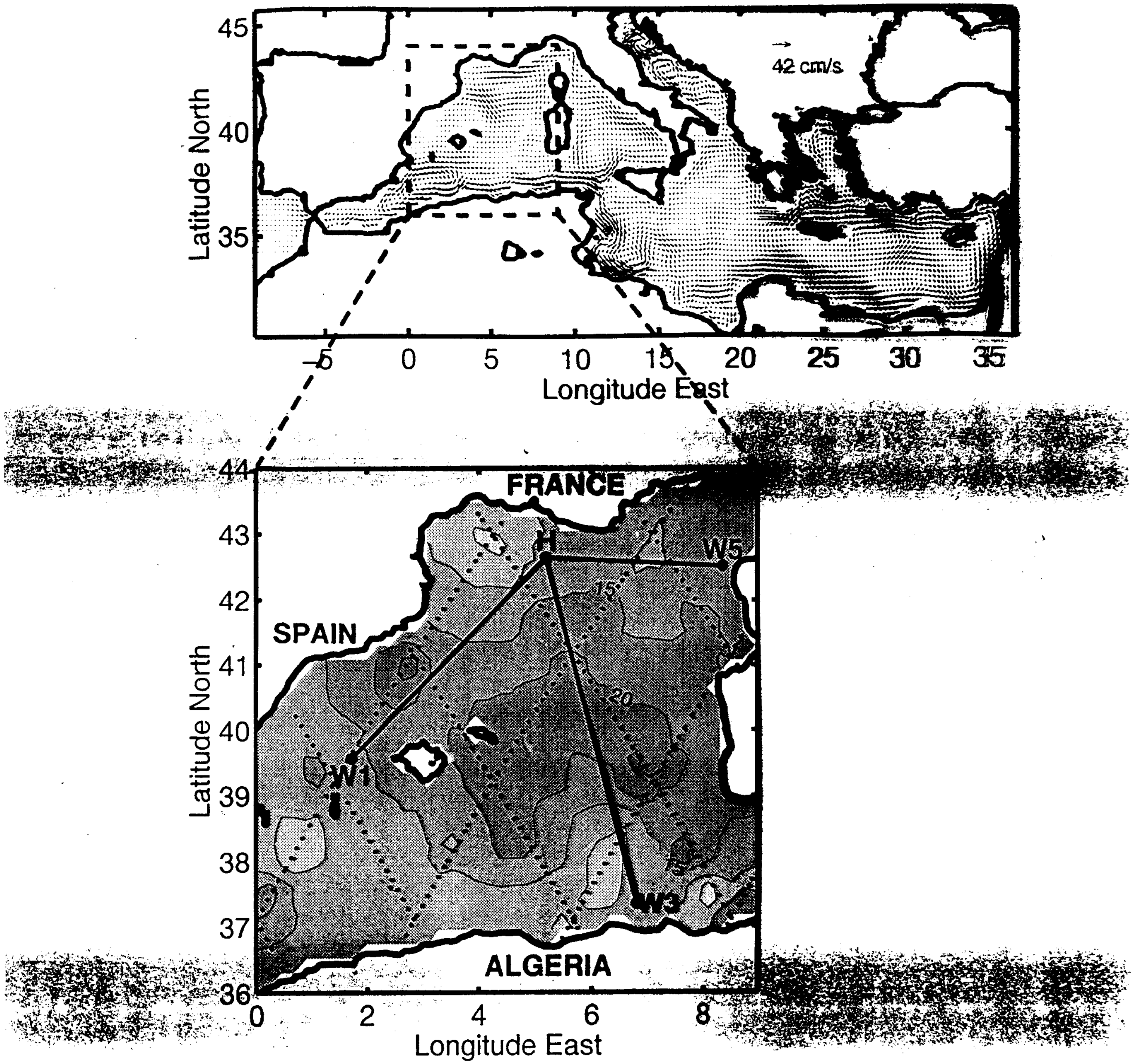
underway

1°, 20-level, 5-year adjoint model computation

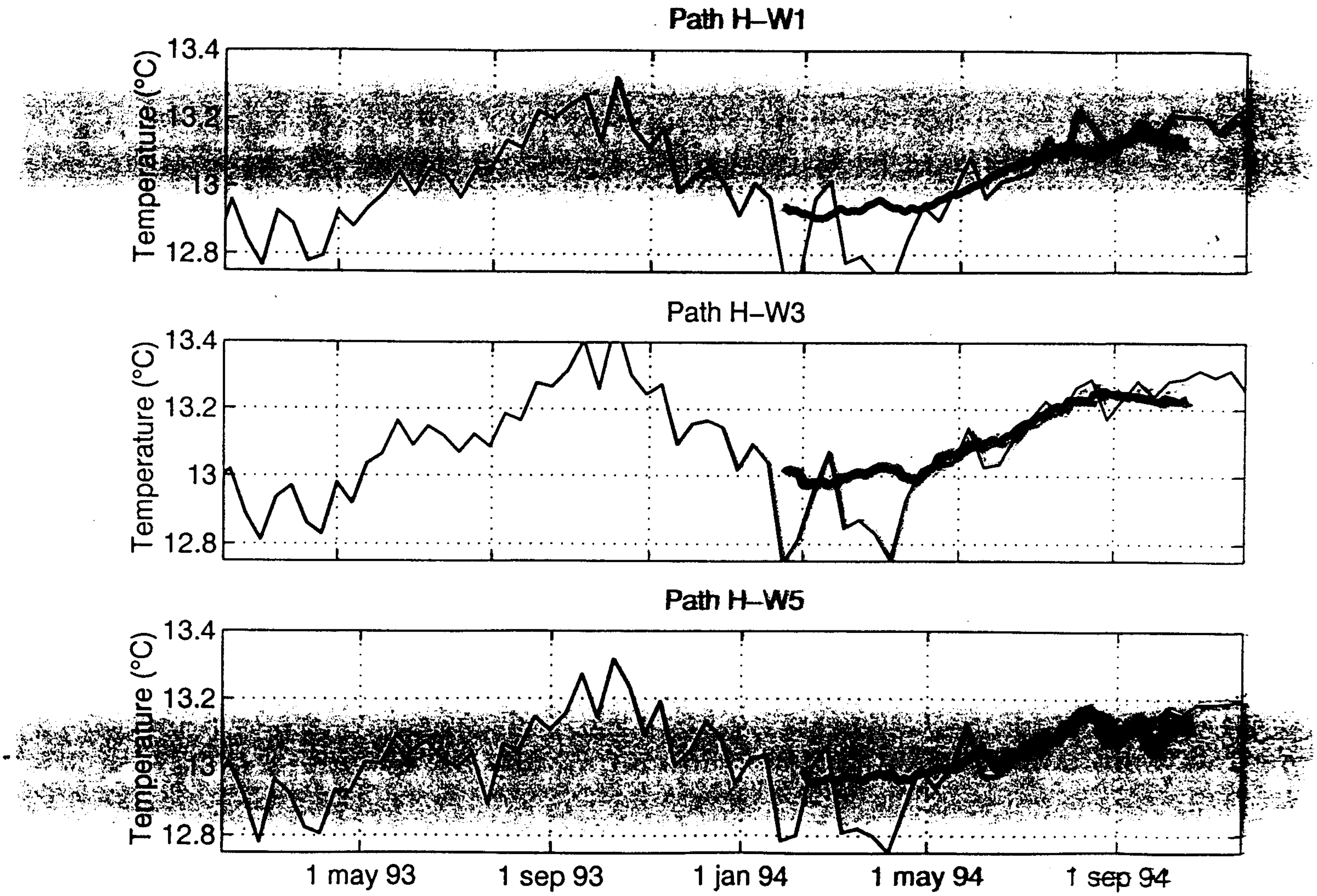
1° → 1/3°, 46-level, KPP, GM forward integration

proposed to NOPP

1985 - 2000 optimization, eventually at 1/4° global.



(Menemenlis et al. '97)



(Menemenlis et al. '97)

Estimation problem

GCM errors:

$$\mathbf{p}(t) = \mathbf{x}_{\text{GCM}}(t) - \mathbf{x}_{\text{ocean}}(t)$$

Dynamical model:

$$\mathbf{p}(t+1) = \mathbf{A}\,\mathbf{p}(t) + \mathbf{q}(t)$$

Measurements:

$$\mathbf{y}_{\text{data}}(t) = \mathbf{H}(t)\,\mathbf{x}_{\text{ocean}}(t) + \mathbf{r}(t)$$

Residuals:

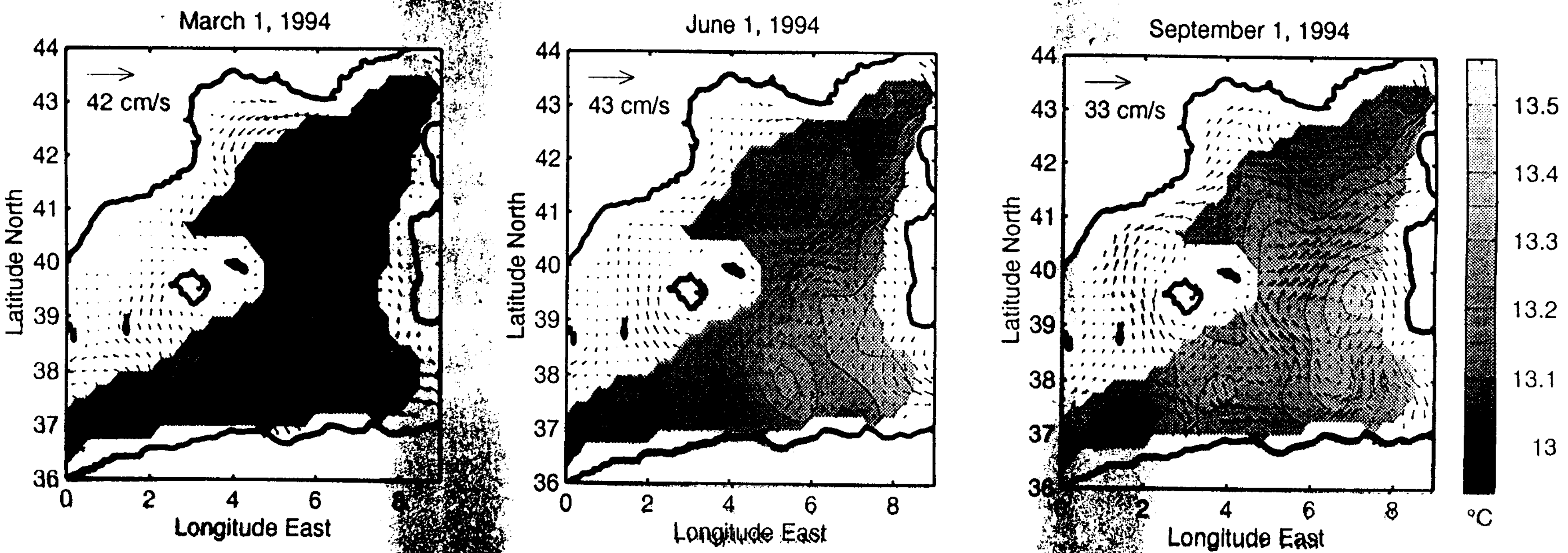
$$\begin{aligned}\mathbf{y}(t) &= \mathbf{H}(t)\,\mathbf{x}_{\text{GCM}}(t) - \mathbf{y}_{\text{data}}(t)\\ &= \mathbf{H}(t)\,\mathbf{p}(t) - \mathbf{r}(t)\end{aligned}$$

Covariance matrices:

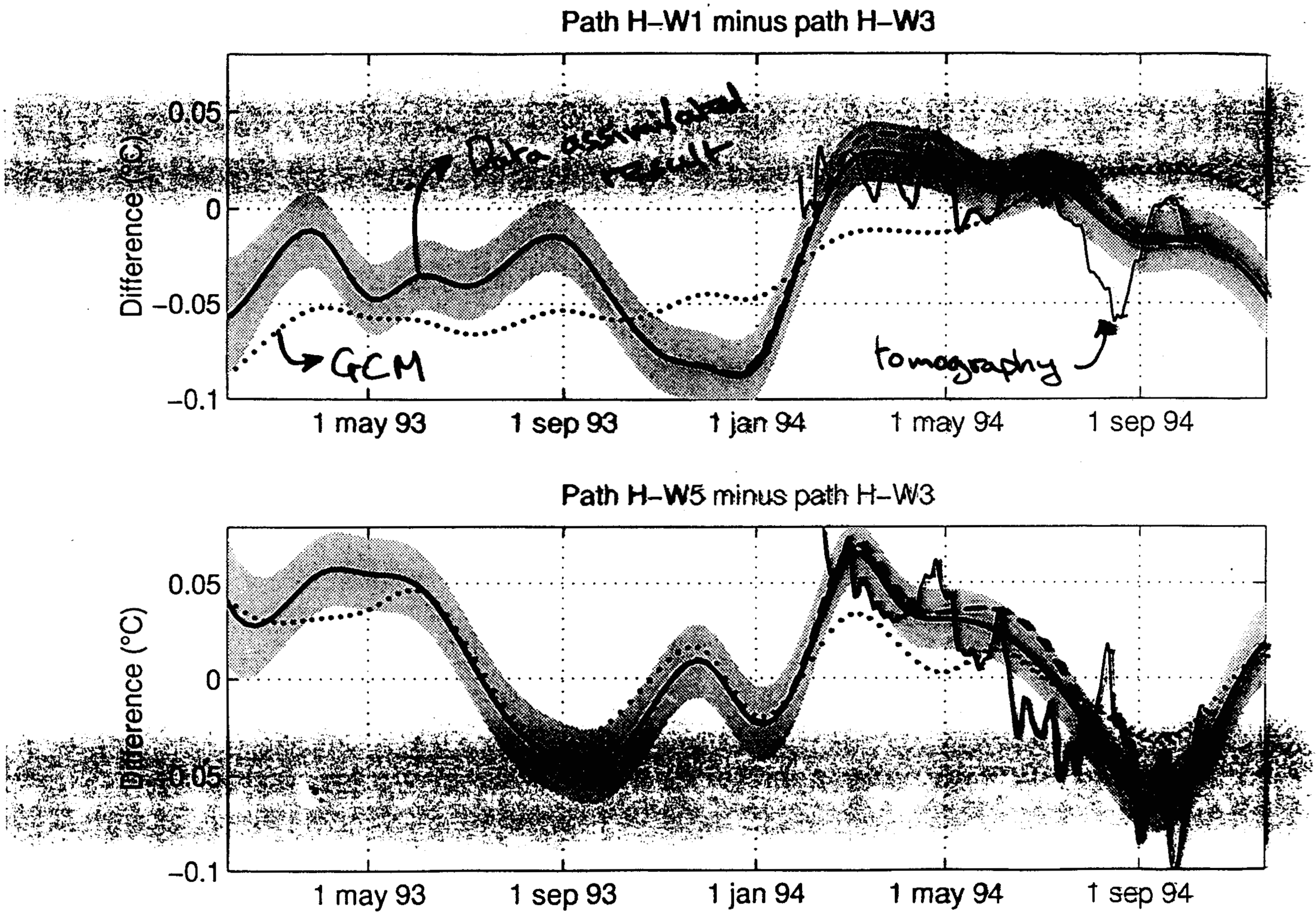
$$\mathbf{P} = \operatorname{cov}\mathbf{p}, \quad \mathbf{Q} = \operatorname{cov}\mathbf{q}$$
$$\mathbf{R} = \operatorname{cov}\mathbf{r}, \quad \hat{\mathbf{Y}} = \operatorname{cov}\mathbf{y}$$

Cost function:

$$\mathbf{J} = \mathbf{p}^T(0)\mathbf{P}^{-1}\mathbf{p}(0) + \sum_t \left[\mathbf{r}^T(t)\mathbf{R}^{-1}\mathbf{r}(t) + \mathbf{q}^T(t)\mathbf{Q}^{-1}\mathbf{q}(t)\right]$$



(Menemenlis et al. '97)



(Menemenlis et al. 97)

rms difference between
η_{altim} and η_{acoust} : 2.4 cm

rms difference between
η_{altim} and η_{XBT} : 2.3 cm

Table 1. Annual harmonic amplitude (in centimeters) and, in parentheses, phase (in days) of range averaged sea level anomaly (η) along the acoustic sections.

Component	Acoustic section				
	l	k	n	o	vT
η_{clim}	2.5 (273)	2.9 (291)	2.1 (284)	2.0 (277)	2.5 (272
η_{acoust}	2.9 (255)	2.5 (257)	2.0 (270)	2.3 (302)	0.8 (59
η_{XBT}					2.7 (304
η_{GCM}	2.5 (262)	3.3 (266)	1.7 (287)	1.0 (270)	0.7 (278
η_{altim}	4.0 (271)	4.9 (276)	4.0 (281)	3.6 (275)	3.6 (282

(The ATOC Consortium '98)

Kinetic energy

Log$_{10}$ of depth-average kinetic energy per unit mass

% barotropic mode

% first baroclinic mode

% second baroclinic mode

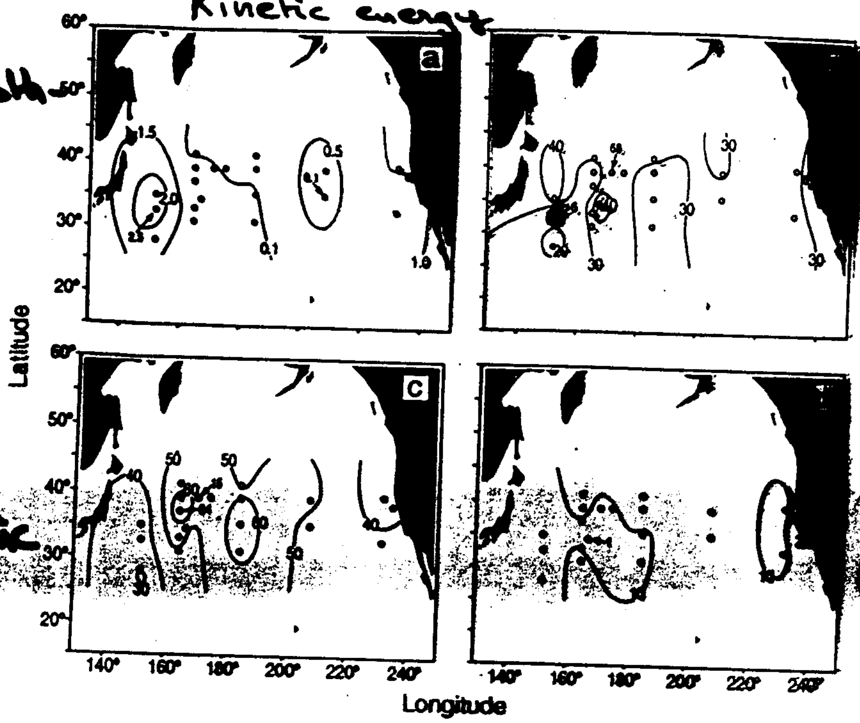


FIG. 5. (a) Log$_{10}$ of the water column average kinetic energy per unit mass in the North Pacific Ocean. (b) Percentage of water column average kinetic energy per unit mass found in the barotropic mode. (c) Percentage of water column average kinetic energy per unit mass found in the first baroclinic mode. (d) Percentage of water column average kinetic energy per unit mass found in the second baroclinic mode.

log$_{10}$ of surface kinetic energy per unit mass

% barotropic mode

% first baroclinic mode

% second baroclinic mode

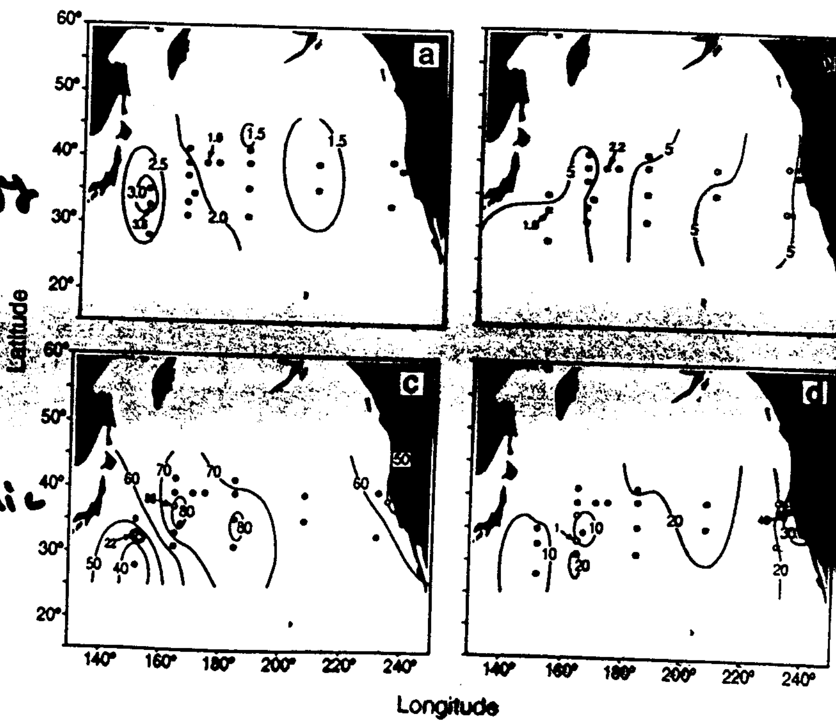


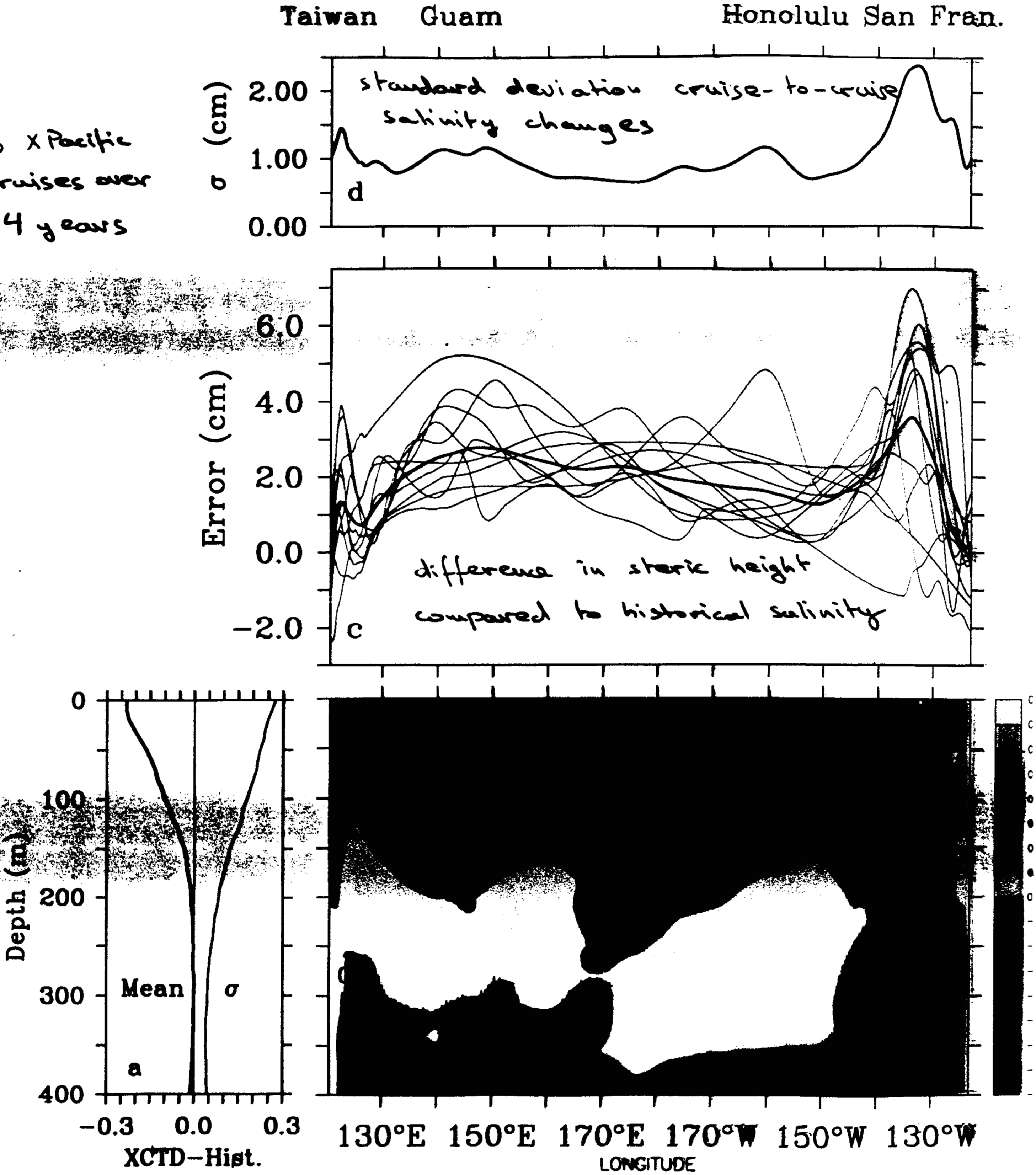
FIG. 6. (a) Log$_{10}$ of estimated surface kinetic energy per unit mass. (c–d) Same as in Fig. 5c–d except for the surface kinetic energy per unit mass $T^{(n)}(0)$. Owing to the surface intensification of the baroclinic modes, little of the surface kinetic energy is barotropic.

(Wunsch '97)

Gilson, Roemmich, Cornuelle & Fu, in pre

SALT ANOMALY

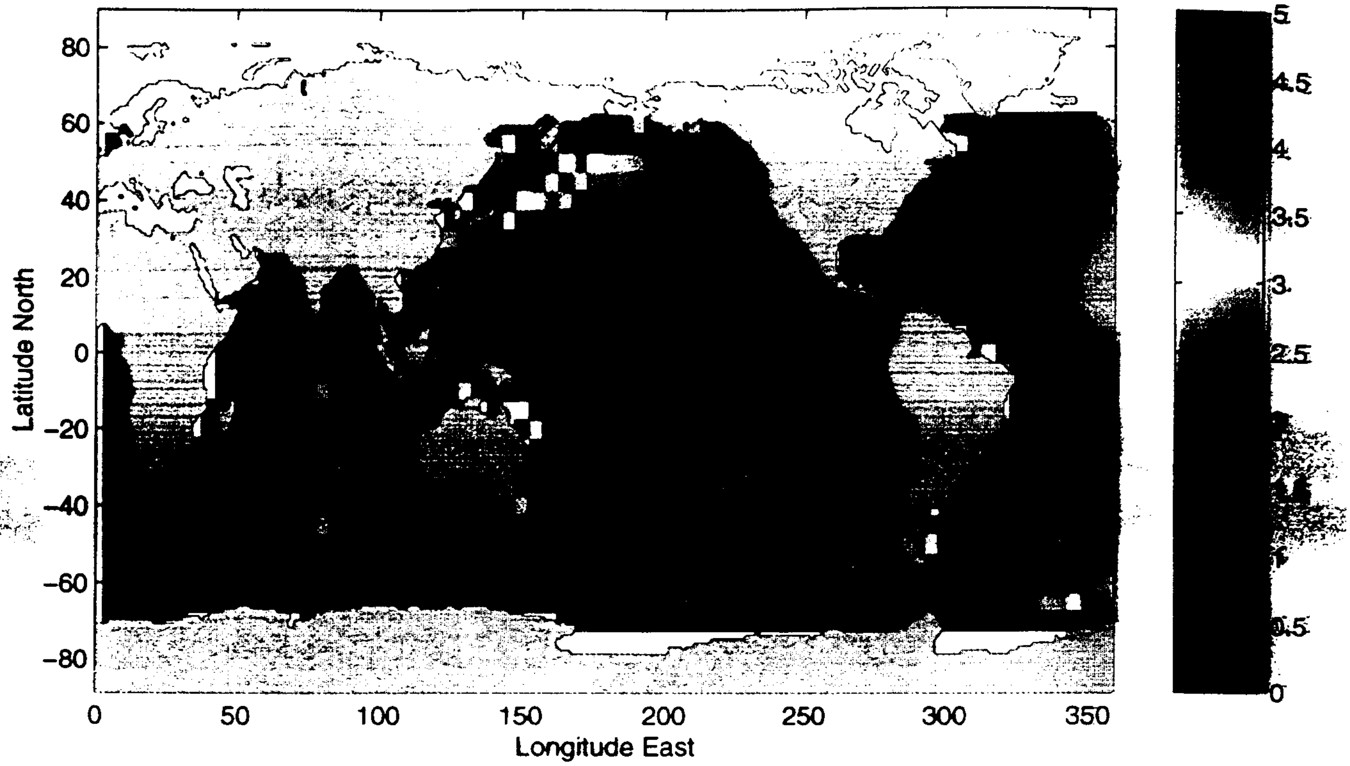
16 X Pacific cruises over 4 years



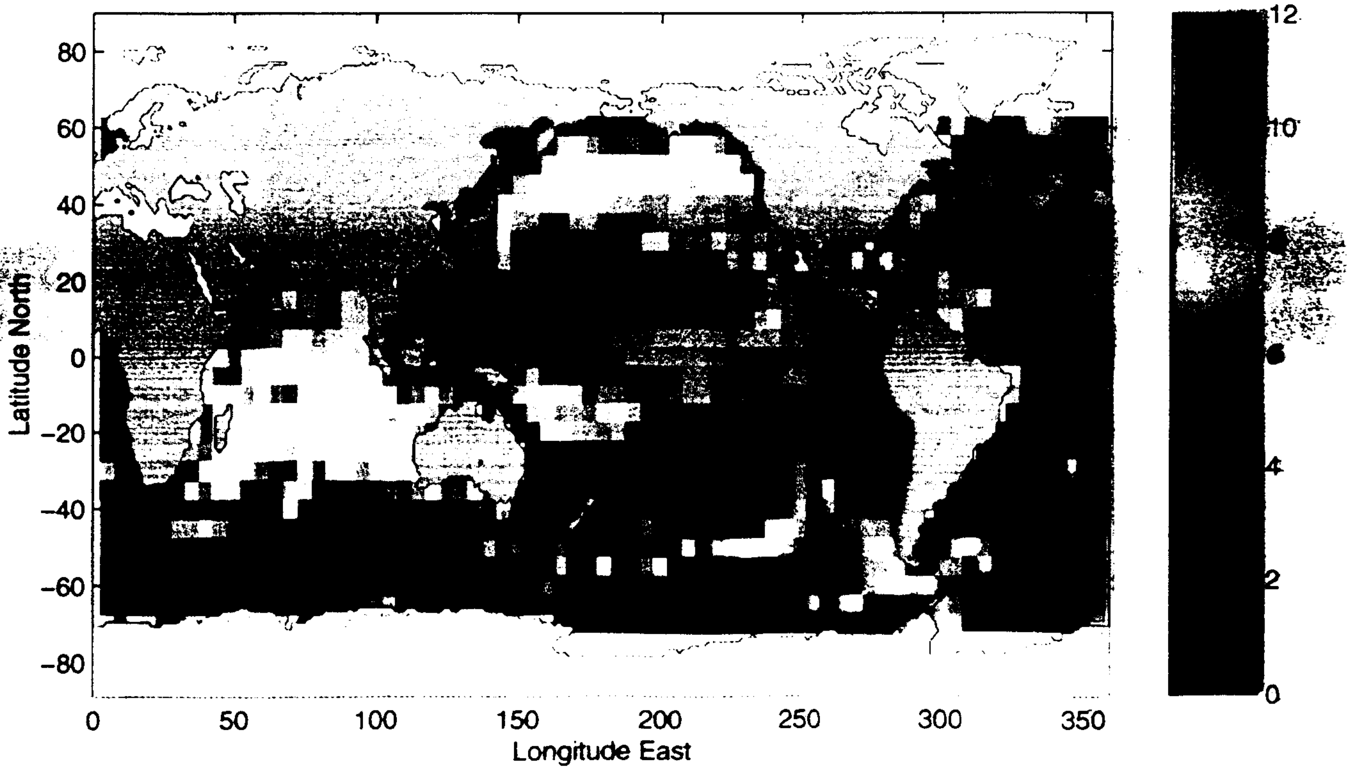
Salinity difference compared with historical data

(Gilson et al. '97)

S&C, barotropic anual harmonic, amplitude (cm)



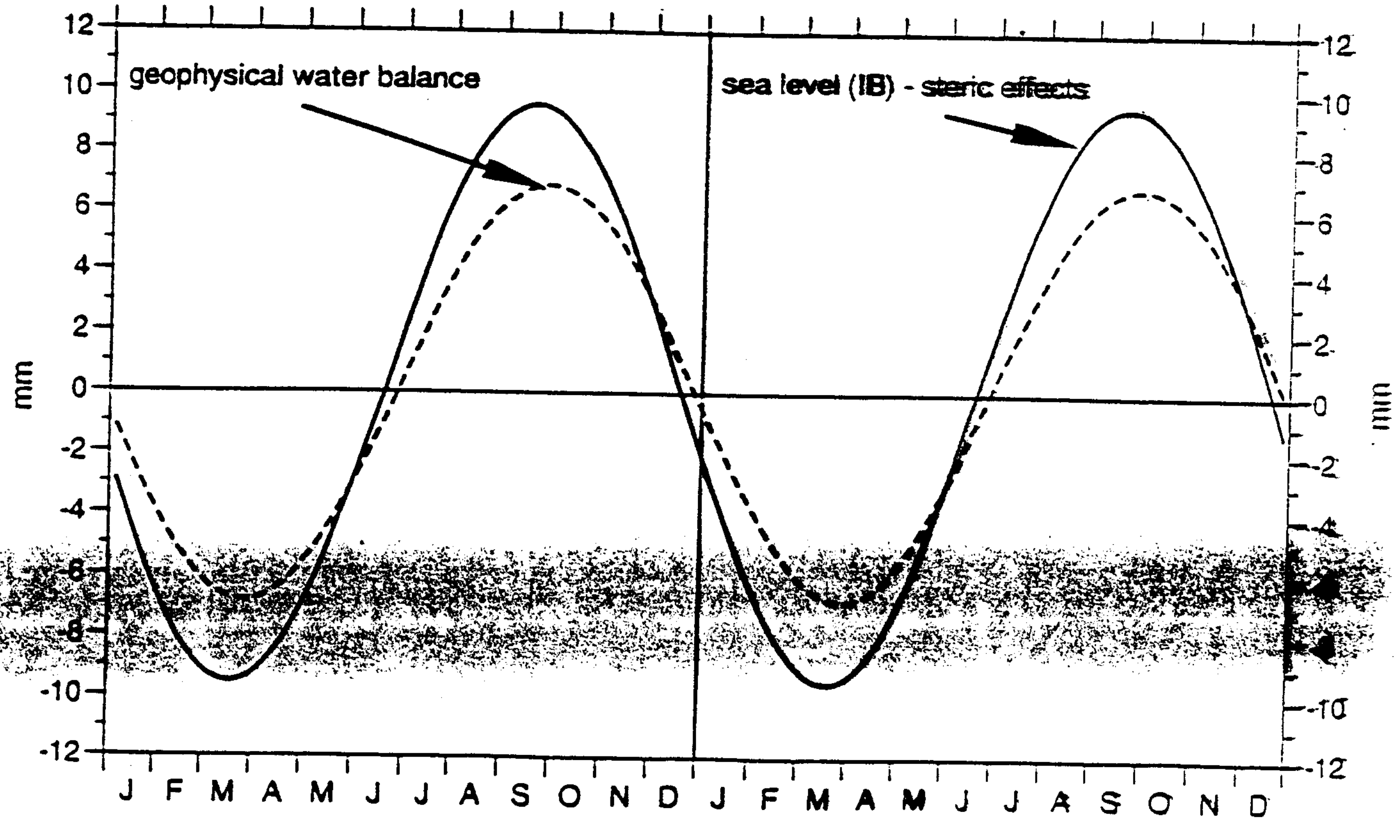
Semtner and Chervin, barotropic anual harmonic, phase (45 deg)



D Menemenlis 10-Nov-1998 23:00 ~/global/model/barotrop.m

$$\Delta M_{ocean} + \Delta M_{water\ vapor} + \Delta M_{continental\ water} = 0$$

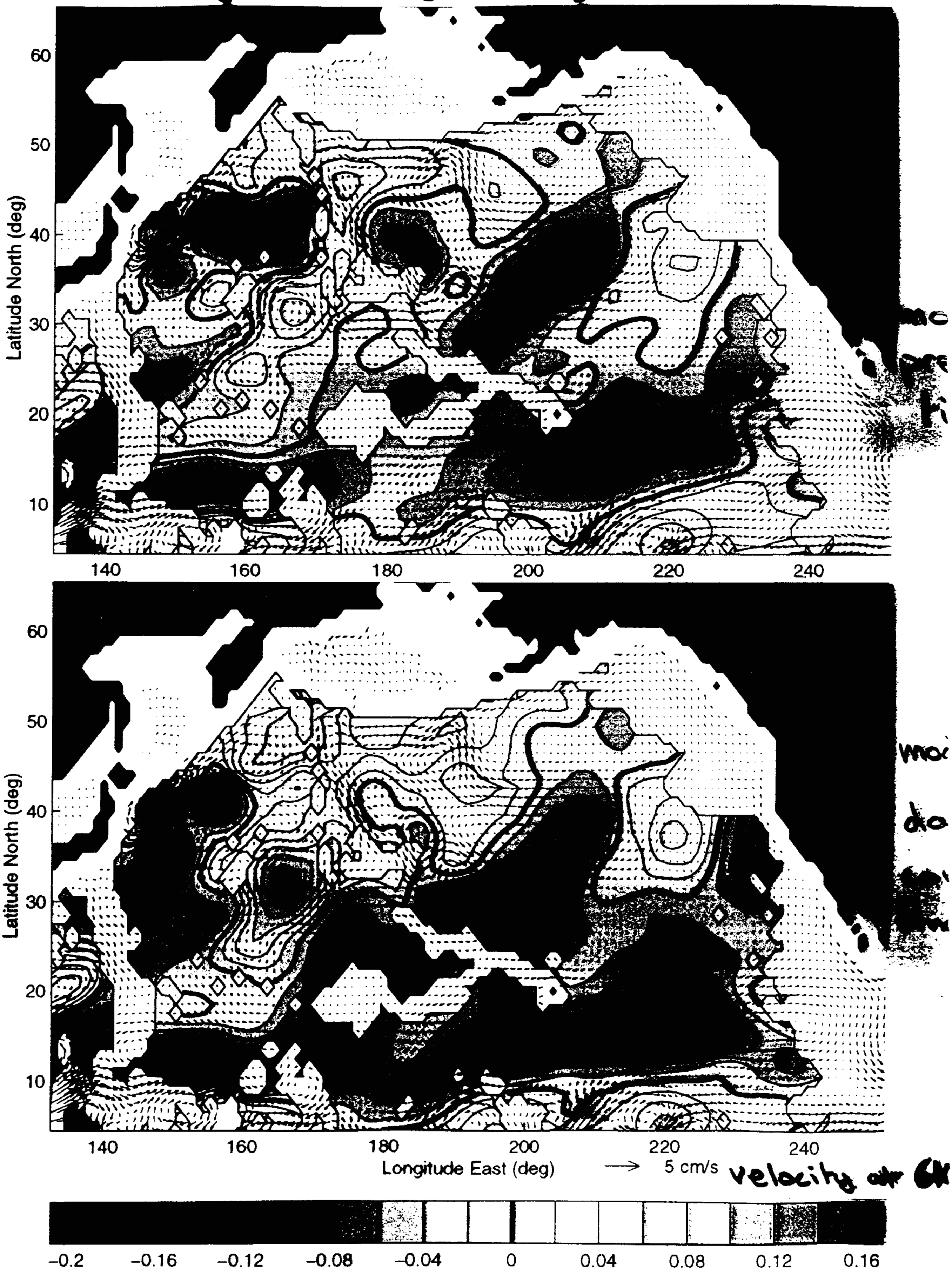
	amplitude (cm)	Maximum
TOPEX/POSEIDON	4.6	Sept. 27
Levitus steric	5.0	March 12
Sea level − steric	9.5	Sept. 19
NCEP Atmospheric water vapor	2.0	Dec. 4
Mintz & Serafini continent water	6.3	Sept. [illegible]
Geophysical Water Balance	6.9	Sept. [illegible]



(Minster et al. 1998)

Fig. 5

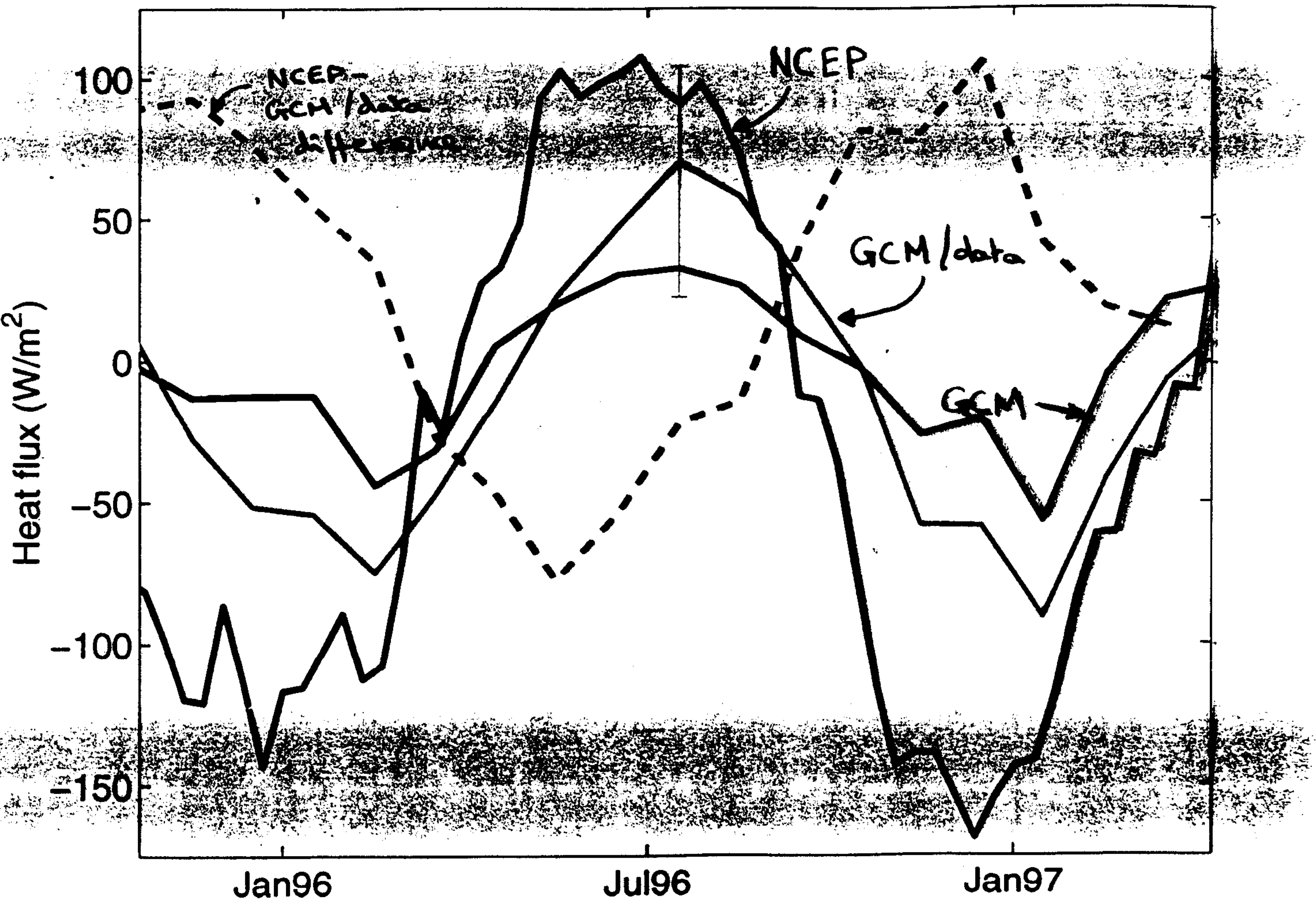
January 97 — January 96



Heat content change in top 4000 m

(ATOC [illegible])

Heat content change in 168°-240°E
16° - 56° N box.

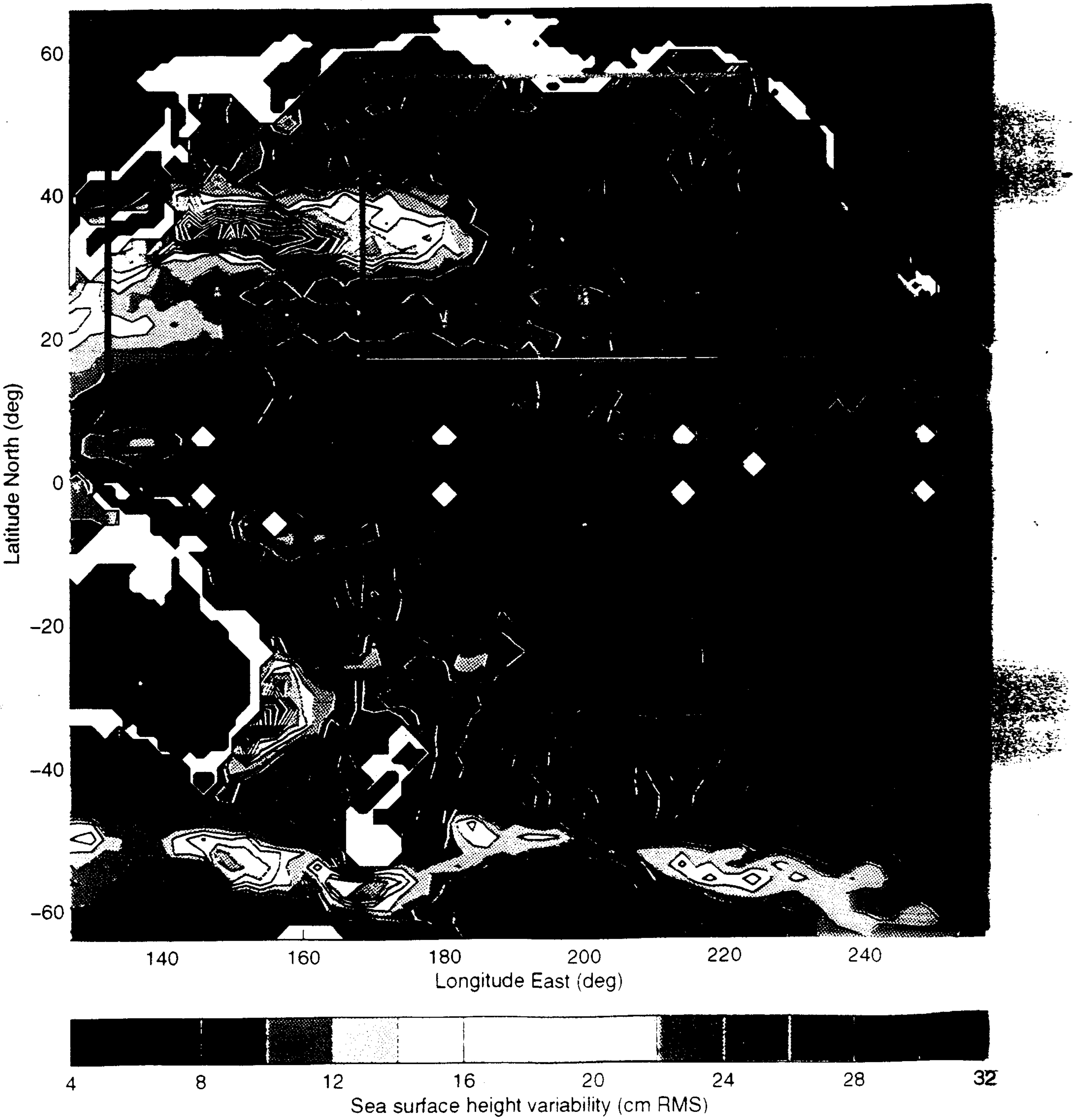


(ATOC Consortium '98)

Concluding Remarks

Acoustic tomography can be an effective data set for understanding general circulation model errors and for testing optimization results.

Global ocean data assimilation system provides a framework for assimilating past and future ocean acoustic tomography data; it also provides boundary conditions for high resolution regional studies.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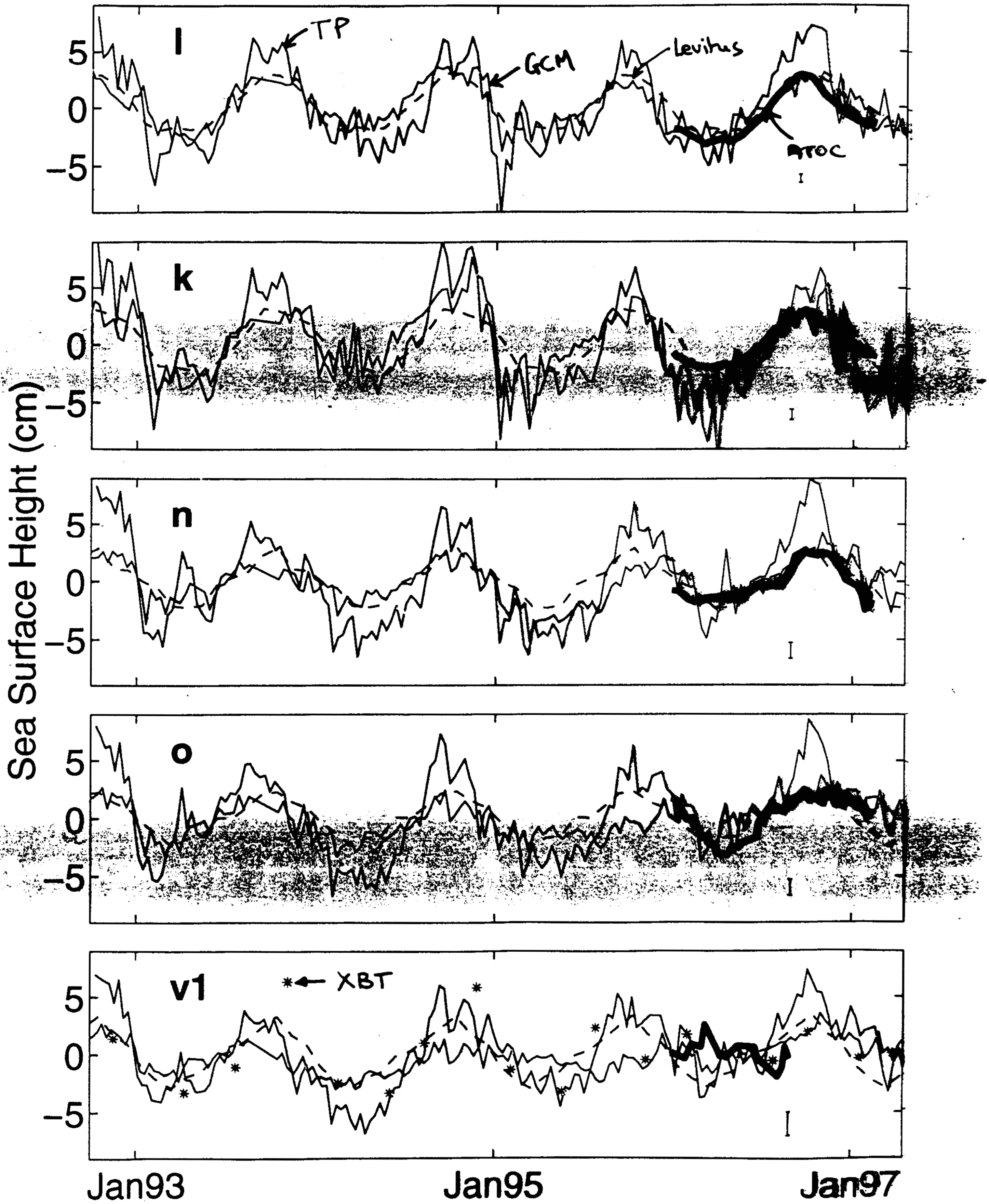
Sea surface height variability (cm RMS)



(The ATOC Consortium '98)

Basin-scale ocean circulation from combined altimetric, tomographic and model data

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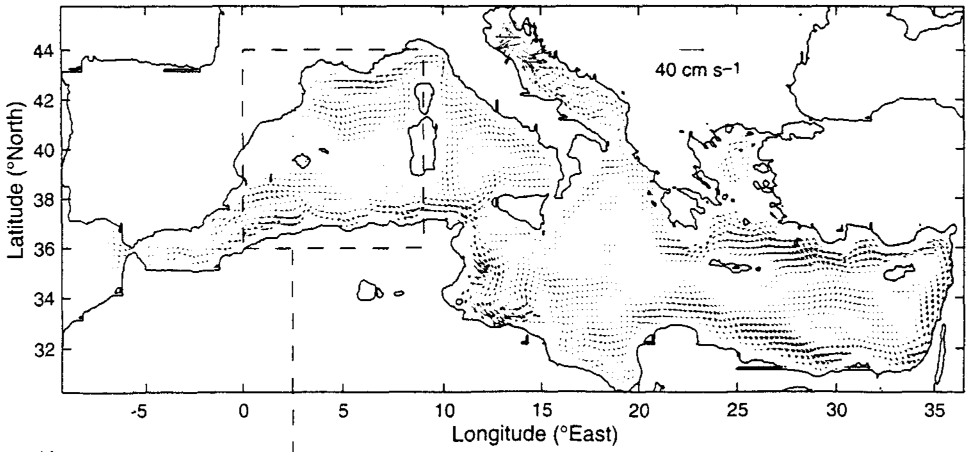
The ocean stores and transports vast quantities of heat, fresh water, carbon and other materials, and its circulation plays an important role in determining both the Earth's climate and fundamental processes in the biosphere. Understanding the development of climate and important biological cycles therefore requires detailed knowledge of ocean circulation and its transport properties. This cannot be achieved solely through modelling, but must involve accurate observations of the spatio-temporal evolution of the global oceanic flow field. Estimates of oceanic flow are currently made on the basis of space-borne measurements of the sea surface, and monitoring of the ocean interior. Satellite altimetry and acoustic tomography are complementary for this purpose[1], as the former provides detailed horizontal coverage of the surface, and the latter the requisite vertical sampling of the interior. High-quality acoustic-tomographic[2] and altimetric[3] data are now available to test the combined power of these technologies for estimating oceanic flows. Here we demonstrate that, with the aid of state-of-the-art numerical models, it is possible to recover from these data a detailed spatio-temporal record of flow over basin-scale volumes of fluid. Our present results are restricted to the Mediterranean Sea, but the method described here provides a powerful tool for studying oceanic circulation worldwide.

The ocean fluctuates on a wide range of spatial and temporal scales[4]. The measured potential-energy spectrum of the circulation is mostly 'red', that is, the energy density increases with increasing spatial and temporal scales, but with a marked peak at the annual cycle. However, the kinetic-energy spectrum is dominated by mesoscale eddies with horizontal scales of 100 km or so, and periods of weeks to months. Therefore, studies of the large-scale movement of the sea need to resolve the mesoscale eddies and other narrow features of the circulation such as boundary-layer jets which are responsible for a large fraction of the heat and property transport. To resolve these features, the ocean would have to be instrumented roughly every 50 km horizontally and at some 20 levels vertically. The requirements for global coverage at this resolution are prohibitive.

Here we focus on the use of tomographic and altimetric observation systems which, in combination with more traditional ocean sampling methods, go far towards solving the global observation problem. Satellite altimetry measures the sea surface elevation relative to the geoid, that is, relative to the particular gravitational equipotential to which the sea surface would conform if it were at rest with no forces acting on it (other than gravity). Changes in



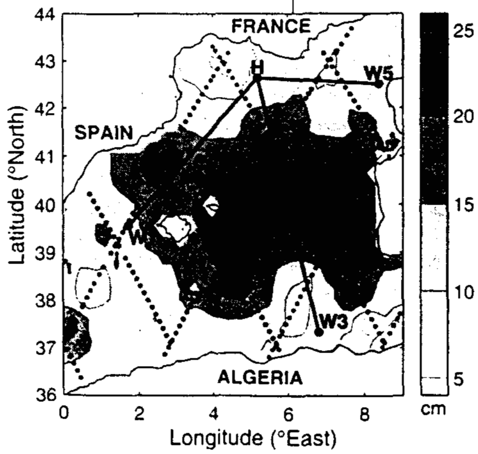


Figure 1 Top panel, the integration domain and the 40-m horizontal velocity on 1 March, 1994 from the Marshall *et al.*[5,6] general circulation model (GCM). Bottom panel, the estimation domain and (contours) the sea level in September 1994 minus the sea level in March 1994, as measured by the TOPEX/POSEIDON altimeter. Dotted lines are altimeter tracks and solid lines are tomographic sections joining an acoustic source H, and acoustic receivers W1, W3, W5 deployed during the THETIS-2 experiment. Mapping of the altimeter data is from a multiresolution optimal interpolation algorithm[7-9]. Estimates have uncertainties varying from ±2.3 cm near the altimeter ground tracks to a maximum of ±4.5 cm between tracks. The mean sea surface height increase is indicative of seasonal warming, but cannot be used to measure absolute heating because of mass fluxes in and out of the basin (flows through the Straits of Sicily and Gibraltar[10], evaporation minus precipitation, and river runoff). Relative changes, for example, the band of higher elevation centred at 40° N, contain contributions from changes in wind forcing and from differential heating and cooling of the water column. The GCM and the acoustic-tomography data are used to separate the respective contributions to sea-level anomaly of wind and heat content.

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SCIENCE

Ocean Climate Change: Comparison of Acoustic Tomography, Satellite Altimetry, and Modeling

The ATOC Consortium